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A VARIABLE BLACKBODY FOR TEMPERATURES TO 4000°K INCLUSIVE

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A VARIABLE BLACKBODY FOR TEMPERATURES TO 4000°K INCLUSIVE

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G. Friede and R. Mannkopff[1]

A variable, well reproducible blackbody is described which consists of an electrical resistance-heated carbon tube, for temperatures from the glow point to the sublimation point of carbon. In the range up to 2300°K, the blackbody radiation could be compared with the response of a Siemens pyrometer; above that, a homemade pyrometer was used for measurements up to the sublimation temperature of carbon. The accuracy of the blackbody temperature setting is determined in practice by the accuracy of the pyrometric temperature measurements. At the sublimation point, there was thus a mean error in the average of 0.15%, corresponding to 6.3°K; with further improvements in the pyrometer system, this error could be reduced at least to 4°K.

1. Introduction

To extend the thermodynamic temperature scale in the pyrometric measurement range, blackbodies at defined temperatures are needed.

The preparation of appropriate blackbodies has been discussed in many studies thus far. Essentially two methods have been used: a) The electrical heating of cavities, e.g. by Lummer and Kurlbaum [1], Magdeburger [2], and Dahm [3], and b) The immersion body method of Hoffmann and Meissner [4] and Tingwaldt and Kunz [5].

The blackbody presented here is a further development of the design of Anacker and Mannkopff [6]. The fixed temperature point is the sublimation temperature of carbon. That we are adding yet another blackbody to the many which have already been suggested can be rationalized in that this radiator encompasses the entire optical temperature range and permits rapid and sure temperature setting as well as long measurement times.

[1]Spectro-Analytical Division of the Mineralogical Institute, Göttingen University.
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2. Electrical System

Arbitrary radiator temperatures require complete freedom in heating current regulation. An adjustable transformer (22.8 kW) of the Ruhstrat/ Lenglern Company was used for this purpose. The primary voltage in the transformer was 380 V, and the secondary voltage was continuously variable from 0-380 V.

Via a lens system, the radiation emitted from the rear side of the glow tube is imaged on a photocell after passing through a color filter. Automatic heating current regulation could thus be achieved: At a certain spectral radiation density (photo-current), the armature current of the servomotor on the transformer was short circuited via a few relays.

Either the blackbody radiation or the radiation from the rear side of the glow tube surface (Fig. 1) can be used to control the heating current.

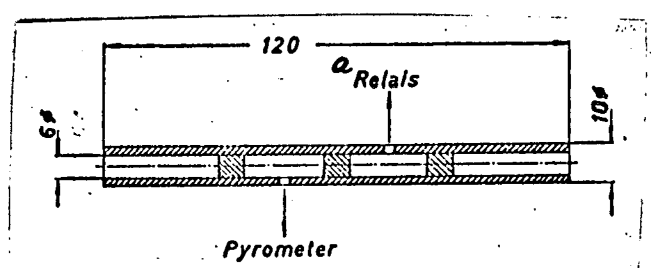

Fig. 1. Carbon glow tube (cross section). Carbon plugs have been inserted in the tube. (Dimensions in mm; ϕ = diam).

a. Relay

If the surface radiation is used for switching, one must remember that the emissivity of the tube surface changes due to structural changes in the carbon tube in the initial phase of the glow process (foreign substances and impurities evaporate up to approximately 5 s after the heating current is switched on). The emissivity remains constant only in the time $t > 5$ s. Whether the initial result is an increase or a decrease relative to the constant value depends on the type of carbon used. Thus, e.g., the hard carbons EK 10 and EK 18 of the Ringsdorff-Werke showed a decrease in emissivity, whereas the high-purity carbon EK 586 showed an increase.

These results can be obtained from investigations of the temporal course of the blackbody temperature, where a repeated heating current regulation occurs for a constant relay sensitivity. It is therefore advisable to clean the carbon tubes initially by pre-glowing.

3. Mounting of the Glow Tubes

The material properties of the carbon tubes necessitate particular attentiveness in their mounting (Fig. 2). The glow experiments have shown that the glow tubes are very susceptible to mechanical destruction. The frequency of breakage increases with the glow temperature. The causes of breakage are the occurrence of internal stresses and the low resistance of carbon to strong local temperture gradients.

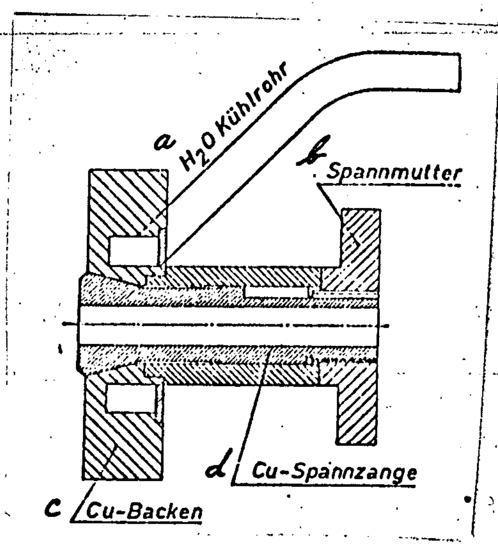

Fig. 2. Chucking and cooling device for carbon tubes (made of copper).

a. H_2O cooling tube
b. Clamp nut
c. Cu block
d. Cu collet

4. Design of Radiator

4.1. Preliminary General Remarks

Since no vacuum apparatus is used here, the main problem in the construction of the radiator is to prevent the glow tube from burning away, which would make the setting of a temperature equilibrium impossible due to the associated resistance change in the tube.

The reducing CO atmosphere which forms primarily at these high temperatures had to remain in the system and its flushing out by strong air currents had to be prevented. It was possible, with the following radiator setups, to stabilize the flow conditions around the glow tube to a great extent, so that burning away can be neglected in the given measurement time and a temperature equilibrium is always attained after a heating period.

4.2. Setup for Temperatures $T < 2300$ K

In this temperature range, access of air oxygen to the glow tube was cut off by mounting one or two protective tubes which were insulated from each other by ceramic rings (sintered Al_2O_3 or MgO) (Fig. 3). The useful limit of this radiator is determined by the melting temperature of the ceramic insulators.

The carbon type best suited for the protective tubes proved to be electrographitized carbon, due to its low ash content. High-purity carbon is best suited for the glow tube, but the cheaper hard carbon can also be used up to temperatures $T \sim 3500$ K.

If these radiators are heated above the melting point of the ceramic, very pure crystalline silicon carbide is formed on the glow tube, as shown by x-ray investigations. Small quantities of SiO_2 are added to the Al_2O_3 by the manufacturer in order to influence the grain size growth.

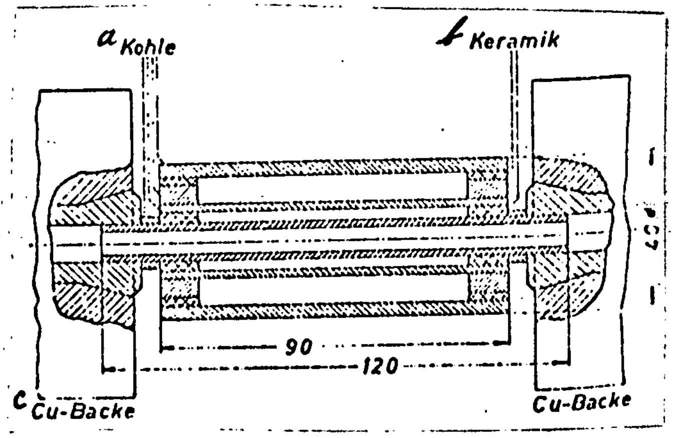

Fig. 3. Cross sectional view of a radiator with two protective tubes (dimensions in mm).

a. Carbon
b. Ceramic
c. Cu block

4.3. Setup for Temperatures from 2300 to <4000 K

Because of current contact, the protective tubes were not allowed to touch the copper blocks. The idea thus suggested itself of putting the glow tube in a housing arrangement (Figs. 4a, b) for temperatures above the melting point of the ceramic. Thin mica discs were placed between the carbon plates and the copper chucking blocks for current insulation.

The air blowpipes in Fig. 4b prevent air from flowing through the radiation exit ports. At an inclination of approximately 6° to the vertical, they develop an additional suction effect by which the air flowing in between the copper blocks, mica disc, and carbon plates is drawn off, and the CO atmosphere inside the protective tube is thus not disturbed.

4.4. Setup for Sublimation Temperature

The illuminating gas/air blowpipe in Fig. 4 now represents an essential component of the apparatus. With these blowpipes, Anacker and Mannkopff [6] were able to prevent carbon, which already re-condensed in the radiation exit

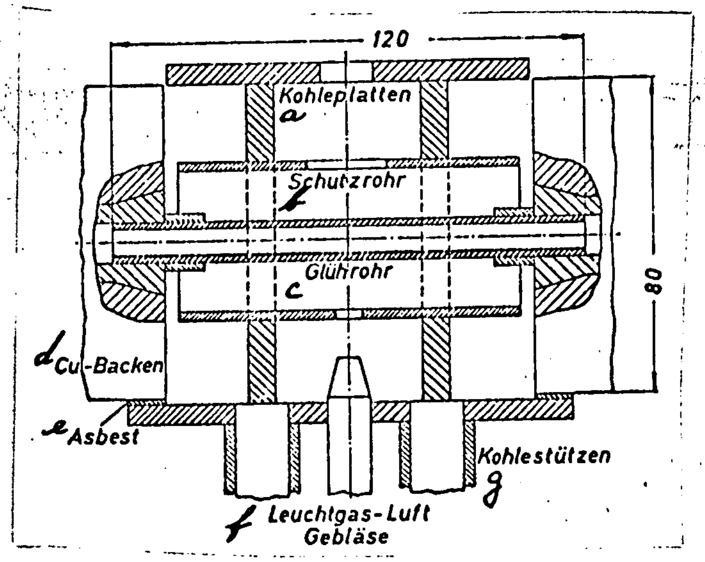

Fig. 4a. Cross section through the housing arrangement. The carbon plates are held by carbon supports mounted on a stand. Carbon sleeves are mounted on the glow tube to the right and left, in order to prevent burning away at these locations. (Dimensions in mm.)

a. Carbon plates
b. Protective tube
c. Glow tube
d. Cu blocks
e. Asbestos
f. Illuminating gas/air blowpipe
g. Carbon supports

port, from plugging the opening. The carbon vapor is blown upward by the high flame flow velocity, and burns there. A detectable absorption of the radiation by the flame is not to be expected.

At the sublimation temperature, even the shape of the radiation exit port becomes important. A circular hole is best suited for pyrometric measurements. However, this restricts the tube cross section perpendicular to the tube axis to too short a piece, leading to breakage of the tubes by overloading at these positions.

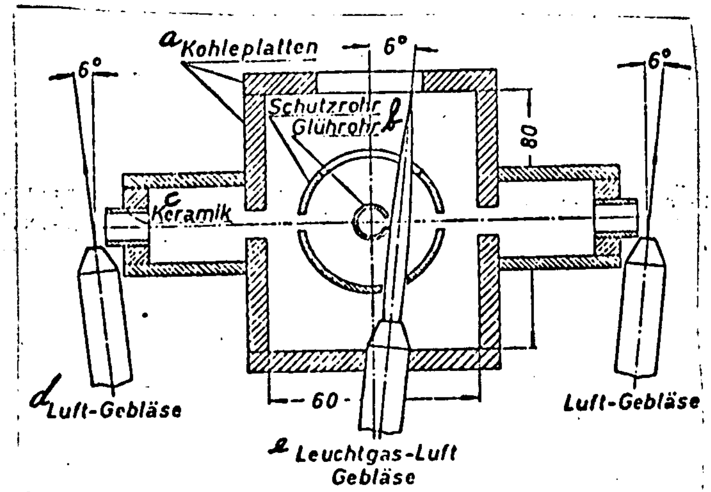

Fig. 4b. Orthogonal cross section to Fig. 4a. The protective tube and housing are slotted open at the top for better venting of the flame gases and carbon vapor. The illuminating gas/air blowpipe is used only for the sublimation. Temperature measurement is made from the right side with the pyrometer. The left opening serves for the relay control of the heating current. (Dimensions in mm.)

a. Carbon plates
b. Protective tube and glow tube
c. Ceramic
d. Air blowpipe
e. Illuminating gas/air blowpipe

Experience shows that the current density in the glow tube must vary only gradually. This condition is met by a slot which is widened in the middle. Furthermore, the cross sectional loss due to the hole was counterbalanced by a collar over the hole, which can be produced by appropriate turning of the tube.

5. The Radiator as a Measurement Gauge and a Standard Gauge

5.1. Setting Time and Radiation Constancy

The setting time to constant temperature, either in heating up from the cold state to temperature T or in adjusting from temperature T_1 to temperature T_2 by changing the heating power, can be adapted to the experimental conditions to a great extent by the experimenter.

The setting time depends on the heat capacity of the glow tube and the protective tube (housing), the size of the predetermined heating current (corresponding to the desired temperature to be measured), and the thermal conductivity of the carbon type.

Table 1 gives information on the conditions pertaining in our case. A more accurate determination of the setting times was unnecessary here.

Part of the blackbody radiation was imaged on a photocell, whose voltage was fed to the vertical input of an oscilloscope. The attainment of radiation constancy was thus easy to determine, and the setting times could also be obtained in this manner.

Another possibility for investigating the temporal course of the temperature in the glow tube is given by the pyrometer and a stopwatch. After the heating current was turned on, pyrometric measurements were carried out in a continuing series, the results of which are shown in Figs. 5 and 6.

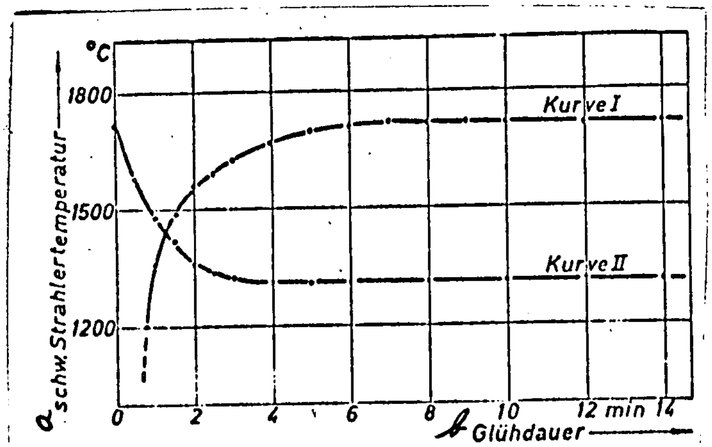

Fig. 5. Blackbody temperature as a function of glow duration. Curve I shows the heating process from the cold state to temperature T; Curve II shows the decrease from T_1 to T_2 (Siemens pyrometer; radiator design according to Table 1, Line 1).

a. Blackbody temperature
b. Glow duration

Table 1. Setting time and measurement time for the radiator types in different temperature ranges. (W_i = wall thickness of inner protective tube; W_a = wall thickness of outer protective tube; W_p [Translator's note: Subscript uncertain] = carbon plate thickness; Sub. T. = sublimation temperature; min = minutes; sec = seconds)

a Strahlertyp	b Einstellzeit kalt zu T	c Einstellzeit T_1 zu T_2 ($T_1 > T_2$)	d Meßzeit	e maximale Meßtemperatur
f 2 Schutzrohre W_i = 2—3 mm W_a = 5 mm	6 min	4 min	20—30 min	2300° K
2 Schutzrohre W_i = 2—3 mm W_a = 2—3 mm	4 min	2 min	20 min	2300° K
g 1 Schutzrohr W_a = 2—3; 5mm	20—60 sec	10—30 sec	20—30 min	2500° K
h ohne Schutzrohr; nur mit untergesetztem Halbrohr und Halbkasten	10 sec	< 10 sec	2—3 min	i knapp unter Sub. T.
j Kasten mit Schutzrohr W_i = 5 mm W_p = 10 mm	5 min	3 min	10 min	knapp unter Sub. T.
k Aufbau analog Zeile 4	< 10 sec	—	10—15 sec	Sub. T.
l Aufbau analog Zeile 5; mit allen Gebläsen	m langsames Aufheizen	—	20—30 sec	Sub. T.

a. Radiator type
b. Setting time, cold to T
c. Setting time, T_1 to T_2 ($T_1 > T_2$)
d. Measurement time
e. Maximum measurement temperature
f. 2 protective tubes
g. 1 protective tube
h. Without protective tube; only with half-tube and half-housing placed underneath
i. Just below Sub. T.
j. Housing with protective tube
k. Design analogous to Line 4
l. Design analogous to Line 5; with all blowpipes
m. Slow heating

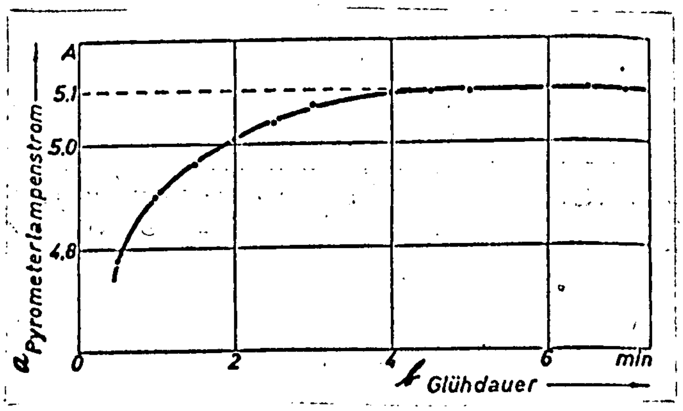

Fig. 6. Pyrometer lamp current strength as a function of glow duration. The constant value corresponds to a blackbody temperature just under the sublimation point. (Protective housing arrangement; heating current 700 A; homemade pyrometer with Wi 9 as lamp; analyzer rotation angle $\phi = 80°$)

a. Pyrometer lamp current
b. Glow duration

As can be seen from Table 1 and Fig. 5, temperature equilibrium is attained faster for the drop from T_1 to T_2 than for the heating up process. It is therefore useful, for consecutive measurements of numerous temperatures, to proceed from the higher values.

With respect to the temperature, the measured values on the curves in Fig. 5 yield a maximum error in the individual measurements of 0.3%. This is within the error limits of the Siemens pyrometer; according to calibration values of PTB-Braunschweig (Federal Physico-Technical Institute, Braunschweig), these limits are $\Delta T = 3$ K in the temperature range 1000-1200° C and $\Delta T = 6$ K in the range $1200 < T < 2000°$ C. For the homemade pyrometer, the maximum error in individual measurements, with respect to the lamp current strength (Osram Wi 9), was 0.6% according to Fig. 6.

Due to the good electrical properties of the adjustable transformer used here and the constant manner of operation of this blackbody, a direct current calibration (assignment of heating currents to blackbody temperatures) can be suggested as a possibility, as indicated by Fig. 7.

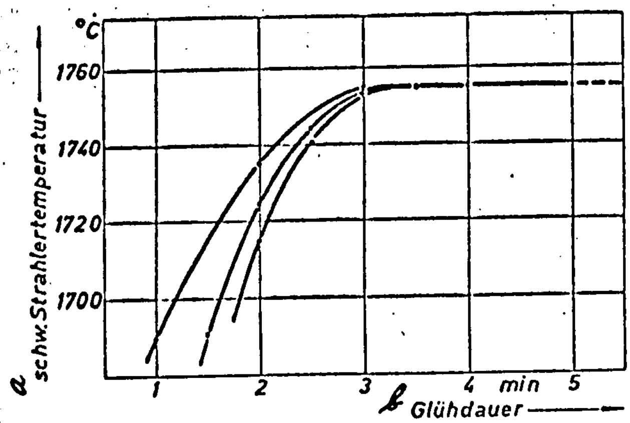

Fig. 7. Blackbody temperature as a function of glow duration for three settings of the same heating current according to the ammeter, and three temperature measurements with the Siemens pyrometer. The different slopes of the curves in the heating phase stem from somewhat different setting speeds on the transformer. (Radiator with two protective tubes.)

a. Blackbody temperature
b. Glow duration

5.2. The Sublimation Temperature As a Fixed Point

Due to the relatively large heat capacity of the protective housing, the procedure for setting the sublimation temperature is as follows: The radiator is first heated for awhile to temperatures somewhat below the sublimation point, and the heating current is then slowly increased until the onset of sublimation can be observed optically through the pyrometer. The formation of lumps of re-condensing carbon on the edges of the hole can easily be seen. A further small increase in the current strength gives the necessary assurance of actual attainment of the sublimation temperature (Table 1, Line 7).

If only half of a protective tube is placed under the glow tube and this arrangement is augmented by a half-housing which is open to the top, measurement times of 10-15 s are obtained (Table 1, Line 6). Since these measurement times are adequate in many cases (e.g. for pyrometric measurements), this simpler arrangement is recommended, since the complete protective housing requires considerable adjusting when inserting new glow tubes.

The measured values in Table 2 were obtained with such a simple arrangement. A new glow tube was inserted for each measured value.

Table 2. Pyrometer lamp current strength i(A) in amperes for sublimation temperature (with error calculation).

i(A) Wi 9	$v \cdot 10^{-2}$	$v^2 \cdot 10^{-4}$
4,02	— 0,7	0,49
4,05	+ 2,3	5,29
4,00	— 2,7	7,29
4,05	+ 2,3	5,29
4,07	+ 4,3	18,49
4,05	+ 2,3	5,29
4,03	+ 0,3	0,09
3,99	— 3,7	13,69
4,00	— 2,7	7,29
4,06	+ 3,3	10,89
3,99	— 3,7	13,69
4,10	+ 7,3	53,29
4,00	— 2,7	7,29
4,00	— 2,7	7,29
3,98	— 4,7	22,09
4,02	— 0,7	0,49
4,05	+ 2,3	5,29
$\Sigma = 68,46$		$\Sigma = 170,93$
	$\bar{x} = 4,027$; $n = 17$	

The measurements were made with a homemade pyrometer in which the intensity of the incident radiation was diminished by a polarization device. The rotation angle of the analyzer prism was set at $\phi = 85°$. This angle was set once and was left unchanged for all subsequent measurements. At the moment of compensation (disappearance of the lamp filament into the radiation background), the intensity of the light emitted by the lamp filament was equal to that of the light coming through the prism. As shown by calibration curves for the lamp Wi 9 (assignment of lamp current strengths to "apparent" black lamp filament temperatures which are still connected with optical losses), which were obtained by means of the Siemens pyrometer and the blackbody, the current strength changes in approximately the same proportion as the "apparent" black lamp filament temperatures in the lamp current range of Table 2.

From the calibration curves, one obtains:

$$\Delta T/T \simeq 0.82(\Delta i/i)$$

From this relationship and the measured values in Table 2, the measured temperature errors in the setting of the sublimation temperature are thus given as follows:

Maximum error in individual measurement:	1.48% ≃ 59 K;
Mean error in individual measurement:	0.68% ≃ 27 K;
Mean error in average value:	0.15% ≃ 6.3 K;

Balancing the pyrometer can be done with considerably greater accuracy with the Osram Wi 22 lamp due to its much thinner filament and its more favorable photometric properties; this is shown by the errors for Fig. 5, which are the maximum errors in individual measurements.

5.3. The Blackness of the Radiator

The important chracteristics for the evaluation of the emissivity of cavities are the shape of the cavity, its reflective properties, and the reflectivity of the wall material. The initial assumption is that there is radiational equilibrium in the interior of the cavity, whose walls are at the same temperature, with only one observation opening.

In our case, however, the tubes are partially open on the side also, and the question thus arises as to the extent to which the open tube ends reduce the blackness. Anacker and Mannkopff [6] assumed that in the case of the sublimation temperature, the tube was also closed on the sides by a soot layer from the just re-condensed carbon, still at the sublimation temperature.

But even at T < 4000 K, the blackness of the radiation will be affected only slightly, since the temperature along the longitudinal axis of the tube will vary only gradually for a tube length of 120 mm. Furthermore, the maximum temperature at the middle of the tube was shielded from the perturbing influence of temperature decay along the longitudinal axis by constrictions (partial turning) in the tube walls.

Thus, even for tubes with open sides, the cavity can, to a good approximation, be regarded as having the same temperature on all sides. Even these considerations are eliminated, however, through the setup shown in Fig. 1.

From a formula given by Bauer [7] for calculating the emissivity ε_H of cavities, the values in Table 3 are obtained as functions of the glow tube dimensions for the radiator used here.

Table 3. Emissivity ε_H of the cavity as a function of glow tube dimensions. ($\emptyset_a$ = o.d. of tube; $\emptyset_i$ = i.d., approximated as the depth of the cavity; r = radius of circular opening of radiation exit port)

$\emptyset_a$ mm	$\emptyset_i$ mm	r mm	ε_H	a Pyrometer-lampentyp (Osram)	b Kohlesorte (Ringsdorff-Werke-Katal.)
10	6	1,0	$0{,}993_5$	Wi 9	Ek 10; Ek 18
10	6	0,7	$0{,}996_8$	Wi 21/22	Ek 586
16	10	1,0	$0{,}997_4$	Wi 9	Ek 18; Ek 568
16	10	0,7	$0{,}998_3$	Wi 21/22	Ek 40
15	12	1,0	$0{,}998_4$	Wi 9	Ek 18
15	12	0,7	0,999	Wi 21/22	Ek 18
				c Kohleplatten	Ek 50

a. Pyrometer lamp type (Osram)
b. Carbon type (Ringsdorff-Werke-Katal.)
c. Carbon plates

The measured temperature errors due to the variable blackness of the radiator were within the measurement precision of the pyrometer, as shown by comparative measurements with radiators of different tube dimensions.

These measurement errors were estimated with the Wien radiation law to be 4 K maximum at the sublimation temperature based on a radiator with $\varepsilon_H = 0.993$ (Table 3, Line 1).

The value $\varepsilon_0 = 0.76$ was taken as the mean emissivity of carbon at $\lambda = 650$ nm, for the calculation of ε_H. The next to last column of Table 3 designates the pyrometer lamps used with the indicated opening radii. The last column designates the carbon types in the individual tube lots.

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